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# A highly polluted marine system in Italy: from the conceptual site model to the preliminary remediation strategies

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## ABSTRACT

The paper deals with an innovative approach to the management of contaminated sites, where geotechnical engineering bridges the gap between site characterisation and addresses for remedial strategies. Such approach has been successfully applied to one of the most critical industrial sites in Europe, which is the marine site of the Mar Piccolo in Taranto (Italy), also declared 'at high risk of environmental crisis' by the national government. The high degree of pollution that has been recorded in the clayey sediments at the sea bottom was found to affect the water quality and promote bioaccumulation of pollutants in fishes and mussels. These findings triggered a governmental investigation campaign to define sustainable remediation actions for the environmental risk mitigation. The site characterisation involved experts from geotechnical engineering, geological, sedimentological, mineralogical, hydraulic engineering, hydrological, chemical, geochemical, biological research fields, who cooperated to gather a new insight into the origin, distribution, mobility and fate of the contaminants within the basin and to define an original Conceptual Design Site Model (CDSM). The present contribution highlights some aspects of such holistic approach, from selected results from the multidisciplinary characterisation of the sediments to some addresses on remedial strategies and few considerations about solidification/stabilisation solutions for polluted sediments after dredging.

*Keywords: multidisciplinary research, marine ecosystem, polluted sediments, environmental remediation, geo-chemo-hydro-mechanical properties*

## 1 INTRODUCTION

This article reports some of the results from recent research entailing a multidisciplinary approach to characterisation and management of contaminated marine sites. In such experience, geotechnical engineering played an emblematic role in bridging the gap between site characterisation and selection of remedial strategies, through the definition of the so-called Conceptual Design Site Model (CDSM). The CDSM, including the processes ongoing within the system, becomes a strategic tool to address both the selection of sustainable remedial strategies and the technology screening phase.

Stemming from the US definition of CSM, as a dynamic tool of increasing maturity to address the selection of remedial strategies, the approach to contaminated marine sites here presented starts from the diagnosis of the system and ends with the first technological screening of remedial options, passing through a central phase of prognosis (Figure 1). The diagnosis consists in a preliminary multiscale, multi-matrix and inter-disciplinary characterisation (Cascini, 2015) to focus on the current state of the system with respect to sources, type and extension of contamination, biocoenosis, geological and hydrogeological setup, geotechnical properties of the sediments and environmental boundary conditions. In the prognosis phase, the CSM has to be implemented with data and integrated results to move towards the CDSM (Figure 1). The CDSM is originally meant to be an updated model including chemical, geo-hydro-mechanical and environmental engineering knowledge about the processes ongoing within the relevant volume of the system. It supports a more sustainable choice of remedial strategies since it is capable of taking account of at least two (Environment and Engineering) of the four-E (Environment, Economy, Equity and Engineering) criteria of the multi-dimensional approach towards sustainability (Basu et al., 2015). Moreover, being centred on the knowledge of processes, this approach can support first predictions of the system evolution, both in the short and in the long term, which would accompany the remediation phase. It is a resilience-based approach, since it encompasses the ability of the system to return to its original state after a perturbation (Holling, 1996, 2001; Walker & Salt, 2006). In the following, after a brief introduction of the contaminated marine site under study, i.e., the Mar Piccolo in the South of Italy, the main phases of the approach outlined in Figure 1 will be presented.

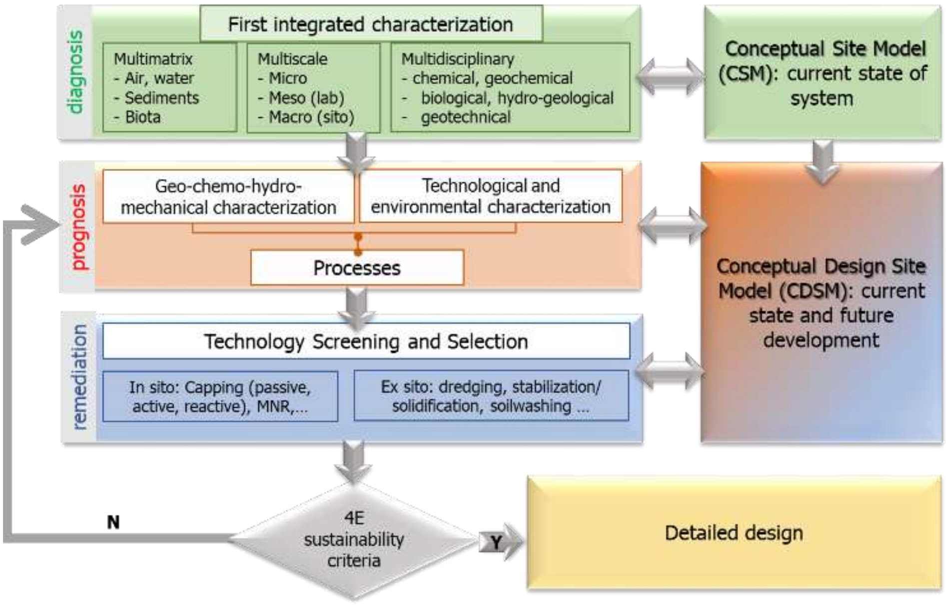


***Figure 1.*** *The integrated approach followed to derive first sustainable remedial options in the Mar Piccolo site.*

## 2 AN EMBLEMATIC CASE OF ENVIRONMENTAL COMPLEXITY

The town of Taranto (Southern Italy; Figure 2) lies within such a highly polluted territory as to be included within the Italian Sites of National Interest, which needs urgently an environmental remediation. In particular, the Mar Piccolo (MP, Figure 2), in the northern part of the town, is a marine basin, for which high contents of pollutants, either heavy metal and organic ones, have been recorded both in the sea water and the marine sediments due to the industrial, naval and urban activities which have caused huge discharges in the basin (Cardellicchio et al., 2007, 2009; ARPA, 2014; Mali et al., 2019). On the other side, for its lagoon features, water circulation characteristics and geological history, the Mar Piccolo is colonised by a complex biocenosis including many protected species of animals and plants. Moreover, the basin is still one of the most important mussel farming areas in Europe, with an annual production of bivalves of about 40,000 tons (Caroppo et al., 2012).

In the case of the Mar Piccolo, the bioavailability of the contaminants has impacted on the various living species, including mussels, to such an extent as to compel the banning of the mussel farming activities (Di Leo et al., 2010). This has been due to both variations in the environmental conditions (e.g. pH, redox potential, microbial activity) which may cause the leaching of the contaminants back to the water column, and hydrodynamic dispersion, remoulding and resuspension of the sediments, which add to leaching in representing the set of processes to be accounted for in the prediction of the contaminant fate and corresponding risks.

The semi-enclosed MP basin has total surface of about 20 km$^2$ and 13 m maximum depth below the sea level. It is connected to the Mar Grande and the Ionian Sea only through two channels so that the water circulation is restricted, and the tidal range does not exceed 30–40 cm (Cecere & Petrocelli, 2009). The water circulation and its features are affected by the presence of several submarine springs (the so-called ‘citri’; Figure 2) and tributary rivers. The clayey sediments in the basin are part of a Late Pleistocene to Holocene deposit, overlying the local geological formation of the Sub-Apennine clays (ASP, hereafter), which represents the parent formation of most of the sediments deposited in the bays (Cotecchia et al., 2021).

Despite such complexity, since the 2010 investigation had been limited to measure degree and typology of contamination in the very top layers of the sediment deposit and did not provide indications about the potential migration over time of the contaminants towards the different environmental sectors of the system (i.e., the water column, the deeper sediment strata, the aquifers and the living species), as well as about the geological and geo-hydro-mechanical set-up of the basin.

Only in 2014, a Special Commissioner for the urgent measures of reclamation, environmental improvement and redevelopment of Taranto (Special Commissioner, hereafter) was appointed by the Government to provide systematic replies about comprehensive environmental issues, e.g., i) deepening the knowledge about the evolution with time of the site pollution; ii) assessing the specific environmental risk; iii) identifying the Mar Piccolo portions requiring risk mitigation interventions; iv) providing addresses to the most sustainable remediation strategies. To this aim, geologists, geophysicists, biologists, chemists, hydrogeologists, geochemists, mineralogists, geotechnical engineers and environmental technologists cooperated for three years in the research study, starting with the design of a cutting-edge investigation campaign in the MP I Bay (Cotecchia et al., 2021). They jointly designed sampling devices and testing strategies to ensure their compliance with the standards for the different testing fields. Thereafter, the whole team ended up with sharing a holistic and interdisciplinary interpretation of the contamination conditions, as advanced support to decision makers in the risk management of the specific site.

Based on a preliminary geophysical survey result, 19 sites were selected for drilling the First Bay. The length of the boreholes varied from 11.6 m to 45.5 m; the bottom of the boreholes was always located at 1.5-3 m depth below the top of the stiff clay formations at the base. Sediments for geological, geochemical, and mineralogical analyses and for chemical testing were sampled by means of polycarbonate liners. Undisturbed geotechnical samples were collected by either Shelby or Denison tube piston samplers within the stiffer sediment strata, while soft sediments were generally sampled by means of the Osterberg hydraulic piston sampler and the thin-walled polycarbonate tube sampler. The latter was manually pushed by scuba divers into the top layer of ultra-soft sediments, 0-1.5 m b.s.f. (Sollecito et al., 2019a).

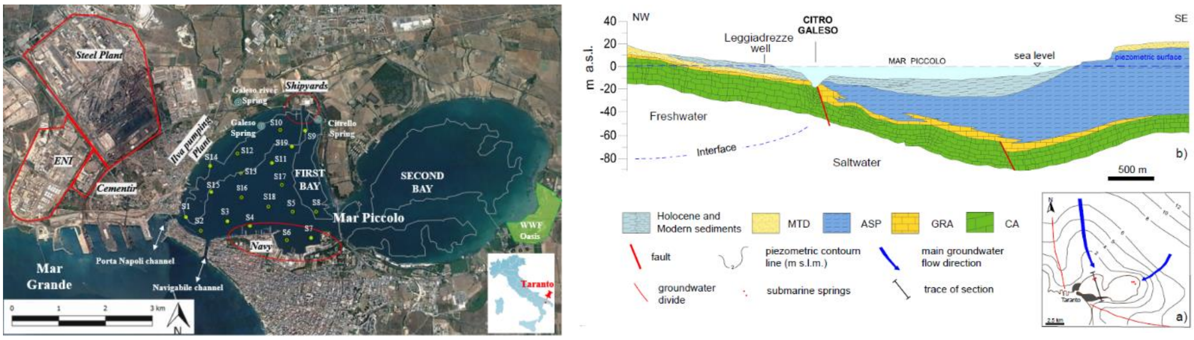


***Figure 2.*** *left: Gulf of Taranto in the South of Italy and MP sampling sites in the First Bay. Key: green areas WWF oasis, grey contours sites used as mussel cultivation areas. Right: Map of the piezometric levels of the deep limestone aquifer (a) and hydrogeological sketch of section (b) whose trace is shown in the map b. Key: CA, Altamura Limestone; GRA, Gravina Calcarenite Formation; ASP, Sub-Apennine Clay Formation, MTD, Marine terraced deposits.*

## 3 BUILDING OF THE CONCEPTUAL DESIGN SITE MODEL

### 3.1 Geological set-up, chemical and biological characterisation

Taranto is located in the eastern border of the Bradano Trough, just west of the Apulian Foreland (Figure 2). In the study area, the Mesozoic carbonate basement of the Apulian Foreland underlies the Bradanic succession (Tadolini & Spizzico, 1996), that is formed of the Plio-Pleistocene transgressive deposits, i.e., the Gravina Calcarenite (GRA) overlain by the Sub-Apennine Clays (ASP). In turn, the succession is covered by Pleistocene to soft Holocene fine-grained sediments, of alluvial, to transitional and marine origin (Mastronuzzi & Sansò, 2003). The morphology of both the MP bays resulted from Late Pleistocene to Holocene erosion processes alternating with sedimentation in marine-coastal, to river, to lagoonal and continental a deposition environment. In recent times, also anthropogenic actions have recurrently caused local disturbance and remoulding of the very top soft sediments, affecting their sequence, especially in the southern part of the First Bay.

The most recent chemical investigation involved the MP sediments up to about 45 m b.s.f. This allowed not only to check the site chemical contamination below 3 m b.s.f. but also to shading light on the evolution with time of the chemical contamination in the top 3 meters of sediments. Specifically, within the sediments, the organic pollutants, metals and metalloids listed in Table 1 together with pH, redox potential and organic matter (OM) were detected. For each tested sediment sample, the contents of pollutants were compared to both site-specific (ICRAM, 2004) and national law (D. LGS. N. 152, 2006) limits (Table 1). According to the pollutants' concentration and distribution, three zones were distinguished in the First Bay of the MP basin (Cotecchia et al., 2021; Vitone et al., 2020). The Chemical Zone a (CZa) in the South contains the most contaminated sediments with the highest concentration of organic and inorganic pollutants, especially within 1.5 m b.s.f., but also down to 3.5 m depth. In particular, polychlorinated biphenils, Hg and hmwHCs (high molecular weight hydrocarbons, C>12) can exceed the law limits, whereas PAHs are always above the site-specific limit. The other metals above the site-specific limit, especially in the first meter, are: Pb, Zn, As and locally, Cu and Cd. The Chemical Zone b (CZb), in the top layers of the central area, is characterised by a concentration of hmwHCs and PCBs lower than those in CZa, but high enough to approach site-specific limits. Hg diffusely exceeds the site-specific limit as well as Pb, Zn and Cu, even if not continuously. At larger depth, Cr and Ni may approach or exceed site-specific limits. Lastly, Chemical Zone c (CZc) is mainly present in the North-East area of the MP First Bay. In this zone, the concentration of pollutants was found below the site-specific limits. For more information about the characteristics of heavy metals, especially toxicity and their distribution in sediment and water in the MP, specific contributions have been published (e.g., Di Leo et al., 2010).

Despite the several anthropogenic pressures insisting on the MP basin, the sediments are colonized by several animal and plant protected species, e.g., the bivalve Pinna Nobilis, the sponge Geodia cydonium, as well as some types of seahorses (Habitat directive EEC Reg. 1992/43; Barcelona Convention and Protocol, 1995). Several Biocoenosis Zones (BZ) were defined. In BZ1 algae at the seabed are either absent or rare, mainly located in the southern and central part of the First Bay. Around this zone and along the western side of the First Bay, BZ2 embraces the seabed covered almost uniformly by macroalgae, where seahorse Hippocampus is widespread. In the northernmost part of the First Bay, the seabed is covered by several species of algae which identify the BZ3.

***Table 1.*** *Concentration limits for soil pollution by organic compounds and metals in mg/kg. a) ICRAM 2004. b) Italian Law n. 152 (2006). Key: PAHs polycyclic aromatic hydrocarbons, PCBs polychlorinated biphenyls, hmwHCs high molecular weight Hydrocarbons, As Arsenic, Cd cadmium, Co cobalt, Cr chromium, Cu copper, Hg mercury, Ni nickel, Pb lead, V vanadium, Zn zinc, nd not determined.*

| | PAHs | PCBs | hmwHCs | As | Cd | Co | Cr | Cu | Hg | Ni | Pb | V | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Site-specific law (a)** | 4 | 0.19 | nd | 20 | 1 | Nd | 160 | 45 | 0.8 | 100 | 50 | nd | 110 |
| **National law (b)** | 100 | 5 | 750 | 50 | 15 | 250 | 800 | 600 | 5.0 | 500 | 1000 | 250 | 1500 |

## 4 FROM CURRENT STATE TO OPTIONS FOR REMEDIAL STRATEGIES

### 4.1 Geo-hydro-mechanical characterisation

Four main geotechnical complexes could be identified on different samples of soils based on the laboratory investigation (e.g., Cotecchia et al., 2021, Vitone et al., 2020; Adamo et al., 2018; Sollecito et al., 2019b; Sollecito et., 2022). Their main features are reported in Table 2. The first complex (C_1) is represented by ultra-soft sediments. They are silty clays of very high plasticity and activity, and their liquidity index is, on average, higher than one. These samples are mainly normally consolidated soils with high compressibility and very low undrained shear strength (BS 5930). Their average effective friction angle is highly variable: between 20° and 34°. As also discussed by Vitone et al. (2016) the higher effective friction angle values measured in these sediments are likely affected by the random presence of shell fragments in the soil matrix and organic matter (OM) that is on average quite high, being equal to 4.35%. The second complex (C_2) is represented by soft sediments: they are less active than the ultra-soft ones and their mechanical properties, both in terms of compressibility and strength, appear to be better than those of the of C_1 (Table 2). Moreover, their average OM content is lower than that of ultra-soft sediments. C_3 is a sandy soil that has been found in the southwestern part of the First Bay. The relative density, $D_r$, ranges between 33 and 59%, that is typical of medium-dense sand. The average peak effective friction angle ($\phi'_p$= 41.5°) of this complex has been determined by combining CPTU and direct shear test results, the latter carried out only when the soil samples exhibited enough cohesion. The fourth complex (C_4) is represented by the ASP Formation. It is essentially made up of silty clays or clayey silts of low plasticity and OM (i.e., PI_$_{AV}$=24.6; OM_$_{AV}$=1.4 %). It is characterised by lower compressibility, higher effective strength and undrained strength than both C_1 and C_2 complexes. Despite the differences in plasticity and activity index recorded between complexes C_1, C_2 and C_4, the mineralogical analyses showed no significant variation with depth of the soil mineralogical composition, except for a reduction in the halite and hematite contents with depth. Within the CF, a widespread presence of illite, interstratified illite/smectite, I/S, and chlorite/smectite, Chl/S has been found. As shown in Figure 3, four Geomechanical Zones (GZ) have been identified within Bay I in the MP basin. They have been distinguished according to the thickness of the complexes with poorer geotechnical features, the depth of the top of the ASP Formation and the presence of sandy soil complex. To each GZ, a class of engineering criticality for the remedial technologies to be adopted has been also associated. The GZ1, at very-high criticality, includes, from the top to the bottom, a 3.5 m thick layer of ultra-soft sediment (C_1) which overlies a layer of soft sediments (C_2) more than 26 m thick. It follows that the top of the ASP Formation (C_4) is found at about 30 b.s.f.. GZ2, at high criticality, is similar to GZ1, but the ultra-soft layer (C_1) is thinner and the intermediate layer includes the sandy soil (C_3; Figure 3). In GZ3, of medium criticality, the top of C_4 is found maximum at 30 m b.s.f., but it is overlaid just by C_2. In GZ4, of low criticality, the top of C_4 is found less than 15 m deep and C_1 is up to 1.5 m thick. Preliminary chemo-hydraulic modelling of the basin has been carried out for different sequences of geo-mechanical complexes and degrees of contamination. The analyses were run under the hypothesis of hydraulic head equal to 1 m above sea level at the top of the calcareous bedrock and considering that the quantity of pollutants measured in the sediments was totally dissolved in the pore fluid. Although this part of the research is still on-going, analytical calculations and numerical modelling using the code SUTRA (Voss & Provost, 2010) gave evidence of the presence of three different Hydraulic zones (HZ) in terms of outflow rate within the First Bay of the basin, depending on both the presence and depth of the top of the ASP formation. Specifically, passing from HZ3 to HZ1 the seepage velocity values have been preliminary computed to reduce from at least 60 mm/year (HZ3) to less than 1 mm/year (HZ1).

***Table 2.*** *Average geotechnical properties of the MP geotechnical complexes. Key: CF_$_{AV}$ clay fraction, MF_$_{AV}$ silt fraction, SF_$_{AV}$ sand fraction, PI_$_{AV}$ plasticity index, A_$_{AV}$ activity, OM_$_{AV}$ organic matter, LI_$_{AV}$ liquidity index, $D_{r\_AV}$ relative density, $C_{c\_AV}$ a compression index, φ'_$_{AV}$ effective friction angle, $C_{u\_AV}$ undrained shear strength.*

| Complex | Description | CF_$_{AV}$ | MF_$_{AV}$ | SF_$_{AV}$ | PI_$_{AV}$ | A_$_{AV}$ | OM_$_{AV}$ | LI_$_{AV}$ | $D_r$_$_{AV}$ | $C_c$_$_{AV}$ | φ'_$_{AV}$ | $C_u$_$_{AV}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | [%] | [%] | [%] | [%] | [%] | [%] | [-] | [%] | [-] | [°] | [kPa] |
| C_1 | Ultra-soft sediments | 46 | 44 | 15 | 56.9 | 1.6 | 4.35 | 2.33 | - | 1.1 | 27 | 5 |
| C_2 | Soft sediments | 36 | 57 | 12 | 28.2 | 0.73 | 1.87 | 1.3 | - | 0.5 | 30 | 50 |
| C_3 | Sandy soil | 11 | 20 | 66 | - | - | 0.6 | - | 46 | 0.05 | 41.5 | - |
| C_4 | ASP Formation | 38.4 | 51.9 | 9.7 | 24.6 | 0.65 | 1.4 | 0.24 | - | 0.24 | 27.9 | 220 |

### 4.2 From the integrated CDSM model to the first selection of remedial strategies

The CDSM of the engineering volume of the basin has been built by integrating the spatial available information about biocoenosis, chemical, geo-mechanical and hydraulic zones. The process started from the superimposition of the available data collected from each sample and borehole coring to obtain geo-chemo-mechanical verticals including the relevant integrated information. The second step was that of associating the boreholes located along specific directions in order to build up integrated sections of the basin (Cotecchia et al., 2021). They have been then combined each other to obtain the CDSM model, according to the approach in Figure 1. Finally, the model has been implemented with the available information about the hydraulic boundary conditions (Cotecchia et al., 1989; Cotecchia et al., 2021) and the biocoenosis layers. In Figure 4 an example of such integration for a single vertical is reported. It includes: i) the site geological features; ii) some of the soil geotechnical data (i.e., composition, plasticity properties and undrained strength) determined by both laboratory and in-situ testing; iii) the chemical measurements. Specifically, the vertical profiles of natural and anthropogenic organic (OM and PAHs, respectively) and inorganic contaminants (Cr and Hg, respectively) are shown. The sandy complex C_3, about 7 m thick, is identified by the soil composition data, the CPTU resistance increasing and the lowering of the average water content. The presence of C_3 addressed the geomechanical zonation of the site as GZ2. It has been also included into CZa, since the concentration of some pollutants is found to be even above national law limits (red vertical lines in Figure 4). Interestingly, in correspondence of the sandy layer (C_3), a reduction of both OM and some inorganic compounds (i.e., Cr) is also recorded. Below this layer, together with an enrichment in fined-grained materials and OM, also a significant increase of Zn, Cr, Ni and V, is recorded, up to concentrations above the site-specific limits. Such high concentrations may be justified by the geological origin of the deep sediments, since they derive from the erosion of the ASP clays outcropping inland. In particular, for the main clay minerals present in these clays, Zn, Ni, V, Cr are generally present in the crystal structure of the clay. Site thresholds for Zn, Ni, Cr should be revised in light of the geological origin of the sediments, i.e., of the site-specific geochemical background. Furthermore, since Zn, Ni, Cr and V are part of the soil skeleton, they are characterised by a lower degree of mobility than the other metals and should not be then considered priority targets in the remediation strategies. It is interesting to notice that at large depth, also the concentration of Cu and, to a less extent, Cd, follow variations similar to those of Ni, V and Cr, suggesting that, in this case, also these two metals might be of lithogenic origin. Lastly, at the seabed of this site algae are either absent or rare (BZ1) and the seepage velocity is less than 1 mm/year (HZ1).

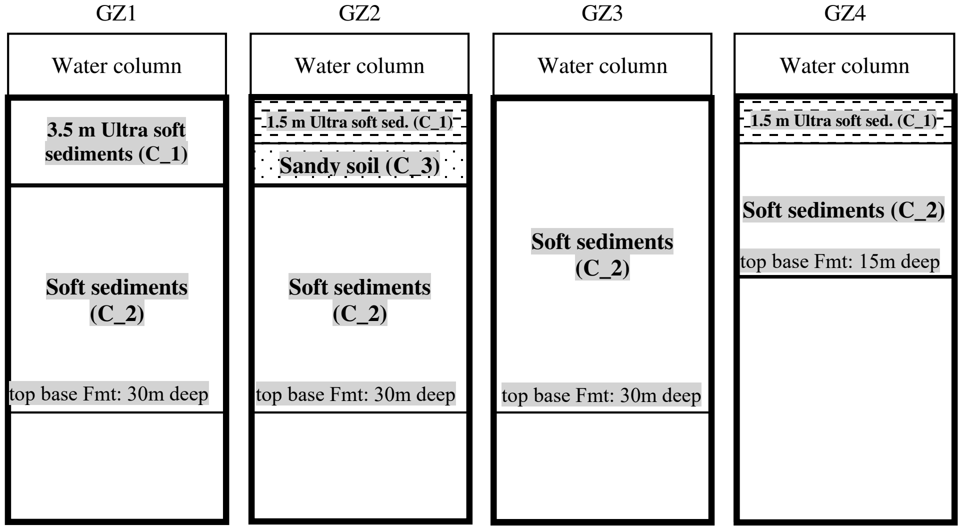


***Figure 3**. Schematic representation of the Geomechanical zones (GZ) based on the geotechnical complexes (C_i) reported in Table 2.*

The CDSM built across the First Bay in the MP site has been used to support an original decision tool which have addressed the customisation of the first selection of remedial options depending on the different environmental zones recognised in the study area. The decision matrix was developed by taking into account the relevant literature (e.g., FRTR, 2002, US EPA, 2019) and based on the integrated approach in Figure 1. It is used to select the management options in function of the environmental resilience of the system. According to Figure 5, the resilience grade of the system can be derived first selecting the Chemical zone and then the Biocoenosis, Geotechnical and Hydraulic Zones of the specific area under study. The first two aspects entail the Environmental part of the four-E sustainable criteria (Figure 1), whereas geotechnical and hydraulic aspects implement the Engineering component in a sustainable approach to remediation. The last two components (Equity and Economy) must be accomplished with in a successive design phase, i.e., at least after having tested the technical efficacy and cost-efficiency of some possible solutions. The resilience of the system is increasing going from grade 1 to 3 in Figure 5. Being the resilience defined as the ability of the system to return to its original state after a perturbation (Holling, 2001; Walker & Salt, 2006), the proposed approach couples stronger engineering-based remedial strategies as far as the system's resilience decreases, i.e., from dredging followed by stabilisation/solidification treatments for resilience grades equal to 1, to MNR and/or bioremediation for areas characterised by resilience grade 3. In particular, when the resilience grade is 1, dredging accomplishes with the need of quick lowering of high pollutants' concentrations (hot spots, CZa). Moreover, the sediments' removal is feasible mainly in BZ1, where protected or sensitive benthic communities are absent or rare, while environmental dredging may be better suited for removal of sediments of high liquidity (geotechnical zones at very high (GZ1) and high (GZ2) criticality. The seepage velocity has little impact on hydraulic or mechanical dredging operations seems not to be a critical factor for selection. For areas characterised by resilience grade equal to 2, in-situ reactive capping is likely the optimising solution for the following reasons: i) in chemical zones of medium pollution (CZb), the dosage of amendment required is still feasible for active capping solutions; ii) the capping technology ensures low community disturbance and preservation of habitats and it is particularly suitable for biocoenosis zones even at intermediate (BZ2) richness in animal and plant species; iii) the high seepage velocity (HZ3) enhances the efficacy of reactive caps that sequestrate and/or degrade contaminants; iv) cap efficacy increases with the lowering of geotechnical criticality, so that capping is most indicated for geotechnical zones of medium to low criticality, i.e., GZ3 and GZ4, respectively. In zones of low/absent pollution (CZc) of resilience grade equal to 3, monitored natural recovery (MNR) and/or bioremediation can be the most sustainable options. However, when polluted zones (CZa or CZb) are associated to rich biocenoses (BZ2-BZ3) and highly critical geotechnical zones (GZ1-GZ2), the areas have multiple resilience grade and, in these cases, the use of coupled solutions is the preferable strategy. For the areas of resilience grades 1-2, some results on ex-situ options of reuse of dredged sediments are presented successively as an example of the activities carried out in the remediation phase in the approach in Figure 1.

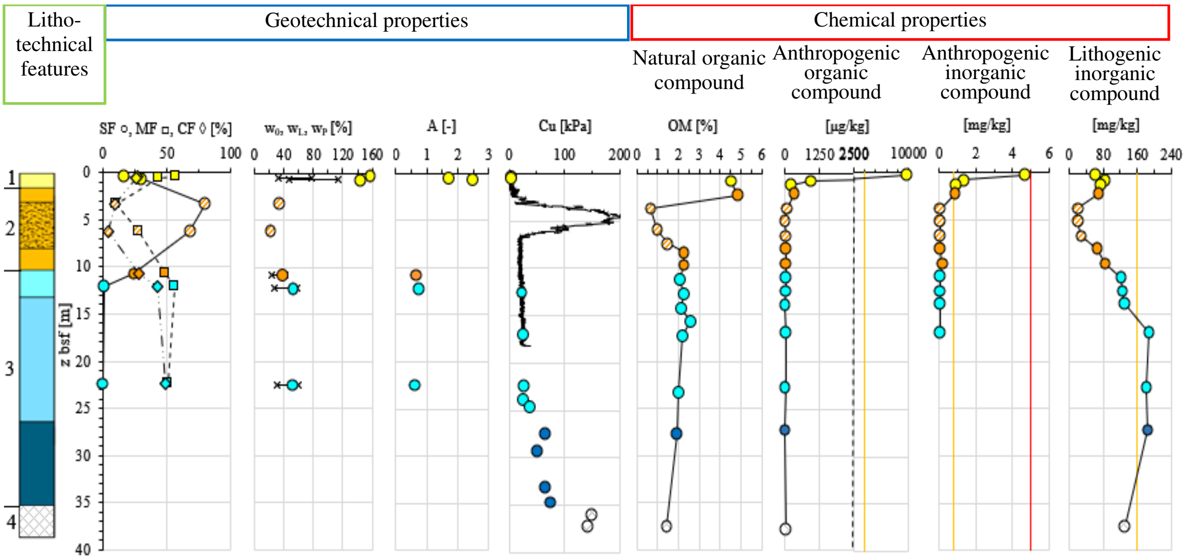


***Figure 4**. Example of geo-chemo-mechanical profile. Key: 1 ■ shallow layer, 2 ■ sandy silt, locally sand, 3 ■ ■ clayey silt from low to high consistency [BS 5930], 4 ■ Sub-Apennine clays (ASP).*

### 4.3 Remediation and Recycling of contaminated sediments

The laboratory testing programme for both the in-situ and ex-situ treatments included chemical, physical and geomechanical investigations. In particular, geotechnical testing has been carried out on the best solutions in terms of chemical performances (Barjoveanu et al., 2018; Todaro et al., 2018) that have been selected among some of the chemo-hydro-mechanical scenarios typical of areas of resilience grade 1 or 2. Geotechnical and chemical investigations were conducted to study the chemo-mechanical effects of in-situ mixing of reactive adsorbent materials with the sediments. Furthermore, the research focused on the effects of ex-situ stabilization/solidification (S/S) treatment with cement and lime enhanced by the addition of reactive adsorbent materials to both reduce the sediments' toxicity and improve their strength prior to ultimate disposal (Wang et al., 2012; Zentar et al., 2012). For the sake of shortness, only some of the results of ex-situ options will be presented (see Todaro et al., 2021 for further outcomes).

The MP sediment sample used for the treatment tests is a fine-grained soil of high plasticity and activity (CF=38%, PI=48.5%), classified as CH according to the USCS classification system (ASTM D2487). It was found to be polluted by both heavy metals (Cu, Pb, Hg, Zn) and organic pollutants (PAHs and PCBs) over the site-specific thresholds (ICRAM, 2004). The sediment sample was treated by adding three different reactive adsorbent materials for in-situ options, organoclay PM 199 (OC; CETCO, Hoffman Estates, IL), active carbon (AC; LIQPRO CS 1100) and biochar (BC), and two binders, CEM I 42.5 R Portland cement (C), and lime (L), for ex-situ solidification/stabilisation options.

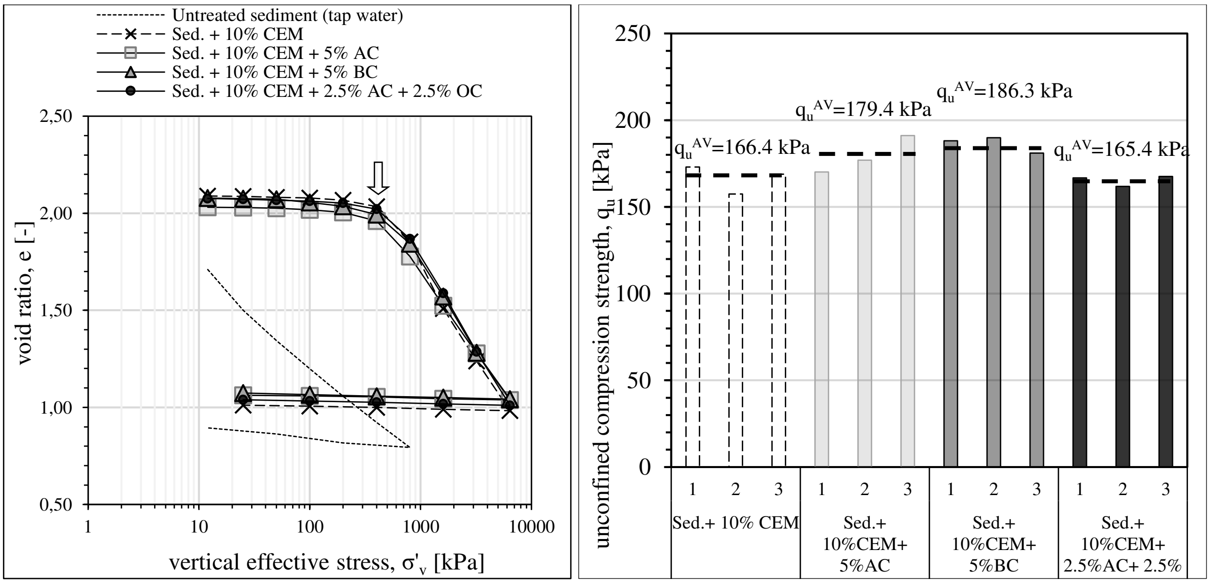
The samples were prepared by mechanical mixing of the sediments with different contents of additives by dry soil weight. For ex-situ treatments (i.e., when binders were used), the mixture water content (w) was always set to 1.2 $w_L$. The quantities of traditional binders and adsorbents mixed to the sediment sample for the geomechanical investigation have been defined after their validation as environmental remediation solutions (Barjoveanu et al., 2018; Roque et al., 2022). The leaching tests (UNI EN 12457-2) have been carried out after different curing times to check if the treated sediments were environmentally acceptable in accordance to end-of-waste criteria (i.e., leaching concentrations lower than law limits of Ministerial Decree N. 88, 1998; Todaro et al., 2020). Few experimental results aiming to assess the geotechnical performance of the selected mixtures are reported hereafter. Figure 6a shows one-dimensional compression results carried out on the untreated sediment specimen, on the specimen treated with cement and on those mixed with cement and adsorbents after 28 days of curing. The e - $\sigma'_v$ compression curves of the treated sediment specimens always lie to the right of the compression line of the untreated sediment. As expected, treated sediment specimens are more stable at higher void ratios than the untreated one, under the same consolidation vertical effective stress. Moreover, the use of adsorbents does not seem to influence the one-dimensional compression behaviour: when either AC or BC are added, the compression curves are almost the same as those of specimens stabilised by cement only. For the treated sediment specimens, the vertical effective stress at yield (Casagrande, 1936) is about $\sigma'_y$ = 500-600 kPa. The average recompression, $C_r$, and compression indexes, $C_c$, are about 0.01 and 0.8, respectively. The results of the unconfined compression strength ($q_u$) tests carried out on cement-treated specimens and sediments mixed with both cement and adsorbents are shown in Figure 6b. After 28 days of curing, the treated specimens exhibit average $q_u$ equal to 174.4 kPa. However, as for one-dimensional compression, no significant variation in strength is recorded when adsorbents are added. Specifically, the maximum average $q_u$ increase (12%) is recorded when BC is used.

## 5 CONCLUSIONS

The research entailed an original approach to contaminated marine sites that has been prompted by the activities led by the Special Commissioner of National Government in the Taranto city (south of Italy), aimed to address sustainable engineering remedial strategies for an emblematic polluted site. The research has shown that the marine basin is a system composed by many constituents interacting in intricate ways and at different scales. Despite their interplay, within the basin, an original Conceptual Design Site Model could be derived by integrating all the information obtained by the holistic investigation and recognising a first zonation of the main characters therein. The CDSM includes not only information on the current state of the system but also on the coupled processes on-going within it and their future evolutions. The CDSM was then capable to support first engineering addresses about the selection of the most sustainable remedial strategies. They have been identified on the basis of a novel decision tool based on the superimposition of the different criticalities recognised within the chemical, biocoenosis, geological, geotechnical and hydraulic zones. These components represent the interplay between Engineering and Environment in a sustainable 4E approach of selection of remedial strategies that takes account of the system's resilience capacity. Moving towards addresses to remediation for those areas of low resilience, few results are also presented as geomechanical promising applications of ex-situ stabilisation solutions for the reuse of polluted sediments after dredging.

| | | ENGINEERING (Geotechnical and Hydraulic Zones) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | GZ-HZ: any | GZ: any - HZ: 1-2 | GZ: any - HZ: 3 | GZ: 1-2 - HZ: any | GZ: 3-4 - HZ: any | GZ: 3 - HZ: 1-2 | GZ: 3 - HZ: 3 | GZ: 4 - HZ: 1-2 | GZ: 4 - HZ: 3 |
| **ENVIRONMENT (Chemical and Biocenonis Zones)** | CZ: a - BZ: 1 | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** |
| | CZ: a - BZ: 2 | **-** | **1** | **1-2** | **-** | **-** | **-** | **-** | **-** | **-** |
| | CZ: a - BZ: 3 | **1-2-3** | **1-2-3** | **1-2-3** | **1-2-3** | **1-2-3** | **1-2-3** | **1-2-3** | **1-2-3** | **1-2-3** |
| | CZ: b - BZ: 1 | **-** | **-** | **-** | **1-2** | **2** | **-** | **-** | **-** | **-** |
| | CZ: b - BZ: 2 | **-** | **-** | **-** | **1-2** | **-** | **2** | **2-3** | **2** | **2-3** |
| | CZ: b - BZ: 3 | **-** | **-** | **-** | **1-2-3** | **-** | **2-3** | **3** | **2-3** | **3** |
| | CZ: c - BZ: any | **3** | **3** | **3** | **3** | **3** | **3** | **3** | **3** | **3** |

***Figure 5.*** *Resilience matrix. Low (1), medium (2), high (3) resilience grades. Key. Chemical zone with high (CZa), medium (CZb) and low pollution (CZc); Biocoenosis zone with low (BZ1), medium (BZ2) and high (BZ3) richness in protected species; Geotechnical zones at very high (GZ1), high (GZ2), medium (GZ3) and low (GZ4) criticality; Hydraulic zones at low (HZ1), medium (HZ2) and high (HZ3) seepage velocity.*



a) b)

***Figure 6.*** *Marine sediment treated with cement and reagents. a) 1D compression behaviour (curing time: 28 days). The arrow is for the vertical effective stress at yield. b) Unconfined compression strength of sediment specimens.*

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